Advanced Transportation System Studies

Technical Area 3

Alternate Propulsion Subsystem Concepts

NAS8-39210

DCN 1-1-PP-02147

Rocket Engine Life Analysis

Task Final Report

DR-4

August 1996

MSFC/Rocketdyne

Rockwell Aerospace
Rocketdyne

TA3–1262

Rocket Engine Life Analysis
Premise

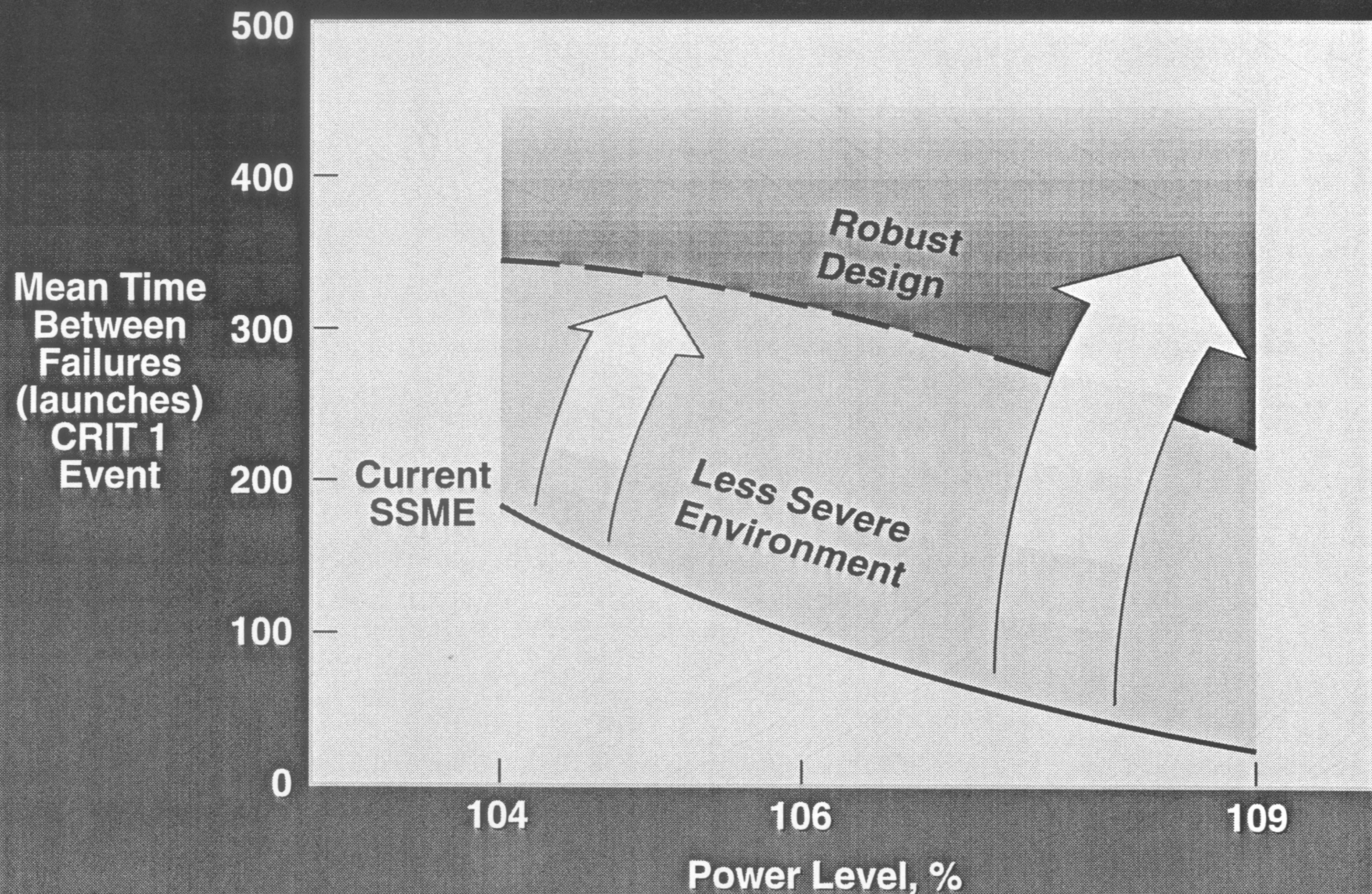
- Most Potentially Viable Highly Reusable Space Transportation (HRST) Solutions Will Have a Rocket Engine Element
- The Rocket Engine is the Element For Which There is the Most Question of Making Long Life
- Only High Performance Rocket Engines are Likely to Apply to HRST
  - Moderate to High I_{sp}
  - Moderate to High Thrust/Weight

TA3–1148a

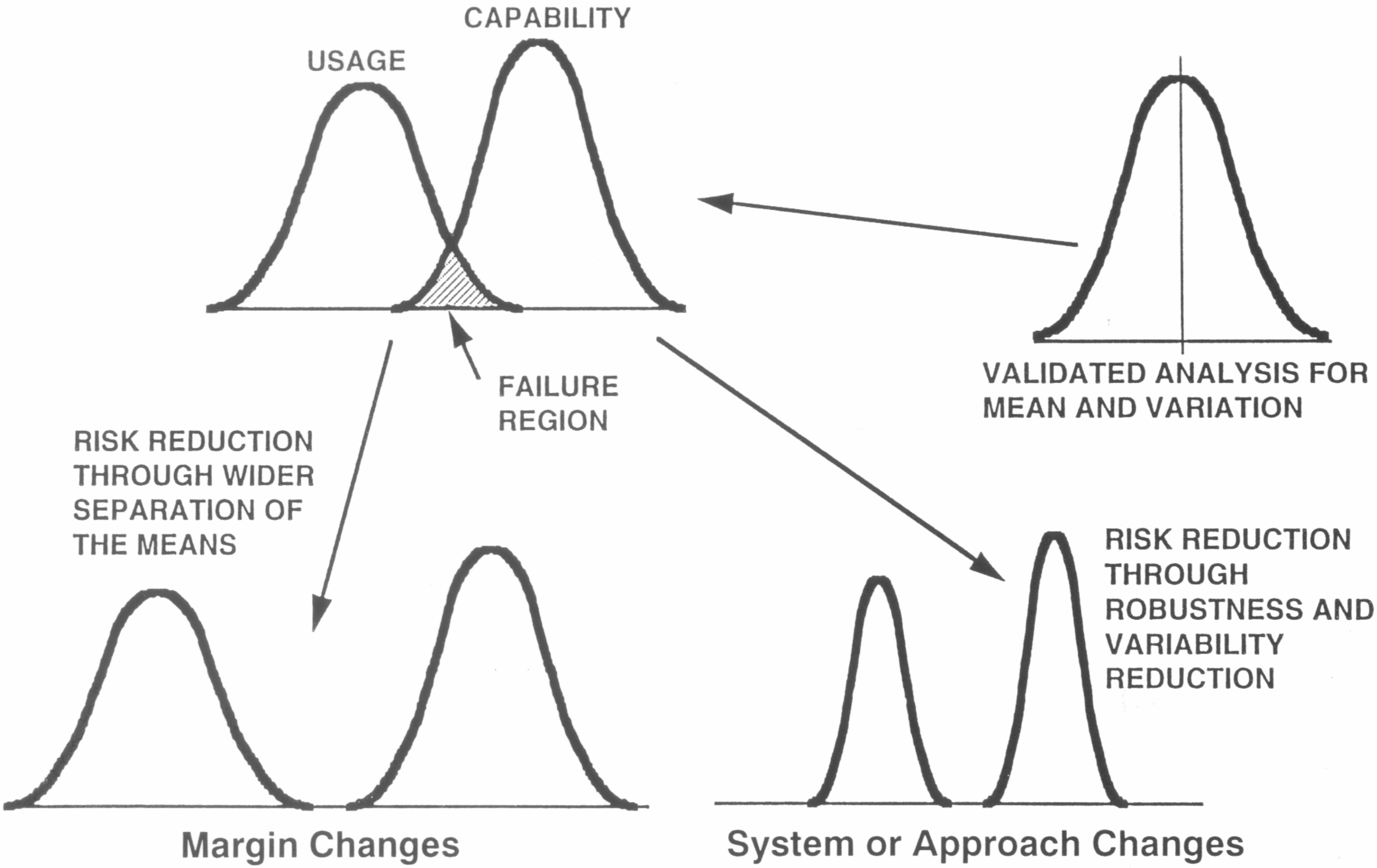
Rocket Engine Life Analysis
Conclusions

- **Methods Are Known to Extend High Performance Rocket Engine Life Beyond Current Reusable Practice**
  - 100's to 1000's of Flights
  - Design Out Life Limiting Lessons Learned from STS/SSME Program
  - Test to Drive Out Failures and Define Operating Limits
  - Less Severe Operating Environment
    - Temperature, Pressure, Flow, etc.
  - Design Power Margin In
    - 10% Provides Very Extended Life
    - Do Not Use Margin for Normal Operations
  - Move to Higher Power Margin Cycles
    - Mixed Preburner, Full Flow Staged Combustion Cycle is the Highest Possible Power Margin Cycle
    - Enlarges Trade Space for All Components
    - Allows Greatly Lowered Turbine and Preburner Temperatures
    - Allows Use of Uncooled Powerhead
  - Use New Technology to Extend Engine Life
    - Turbopumps With Fewer Parts, No Contact Bearings
    - Jet Pumps to Eliminate Low Pressure Turbopumps
    - Laser Igniters and Modified Start and Shutdown Sequences
    - Combustion Chambers with Lower Wall Temperatures
    - New Materials
  - Different Combinations of These Techniques Produce Varying Degrees of Life Extension But All are Not Applicable to All Designs
- **HRST Goal of ≥ 200 Flights Between Propulsion System Overhauls Appears Very Feasible**

Increase in Reliability



Rocket Engine Life Analysis
Two Approaches to Life Extension



Rocket Engine Life Analysis
Design Lessons Learned

- Incorporate Lessons Learned from Past Engines
  - Failure Causes
    - Significant Number Thermally Induced
  - Design Fixes

- Design for Reliability and Robustness
  - Chose Cycle to Improve Margins and Reduce Failure Modes
  - Improves Life

- Test to Drive Out Failures (Engineering Confidence) Instead of Success Oriented Demonstrations (Statistical Confidence)
  - Early Focus on High Risk Areas
  - Complete Characterization of Operating Environment
  - Extensive Limits Testing Conducted at the Component Level
  - Early Introduction of HMS to Characterize HMS and to Preserve Test Assets

Rocket Engine Life Analysis
Design Examples

High Pressure Turbomachinery	• Fluid Film Bearings • Low Temperatures • No Protective Coatings • Advanced Materials • Eliminate Seals and Purges
Low Pressure Pumps • Jet Pumps	• No Rotating Turbomachinery • Fewer, Lighter Lines
Main Combustion Chamber	• Lower Wall Temperatures
Powerhead	• Low Temperatures
System	• Eliminate Purges and Fluid Systems • Eliminate Sheet Metal and Complexity

TA3–1121

Rocket Engine Life Analysis
Agenda

- What Drives Engine Life?
- Reusable Engine History
- Life Extension Approaches
    - Modify Operating Environment
    - Modify System
- Mitigation Approach Summary
- Summary and Conclusions

What Drives Engine Life?

Rocket Engine Life Analysis
What Drives Engine Life?

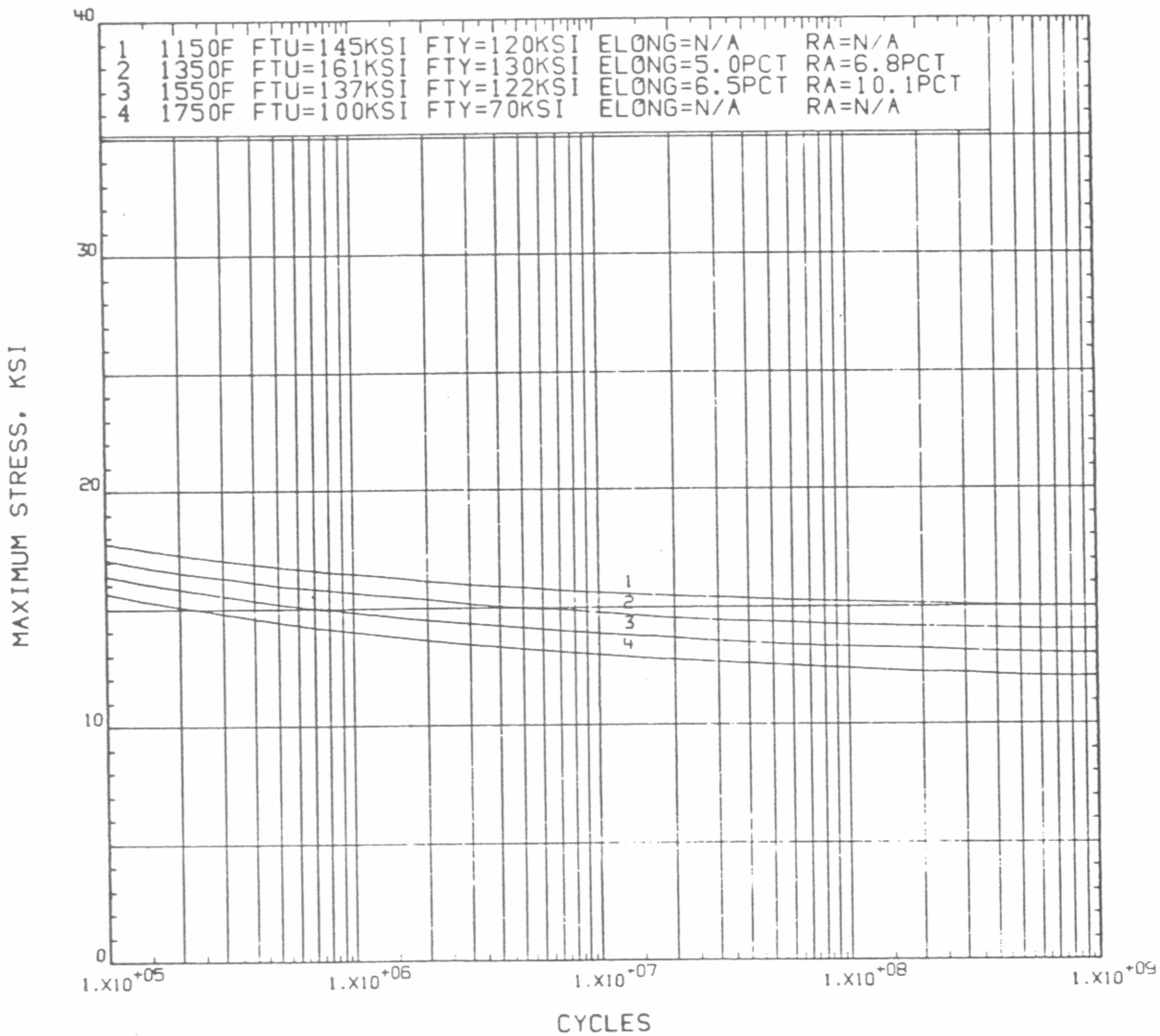
- Reusable versus Expendable
  - Safety Factors
  - Low Cycle Fatigue (LCF) Life Margin
  - Material Selection Considerations

Rocket Engine Life Analysis
Design Safety Factors

	Expendable	Reusable
Proof Factor	1.2	1.2
Ultimate Pressure Load Only	—	1.5
Ultimate Combined Loads	1.4 - 1.5	1.4
Yield Combined Loads	1.1	1.1
Low Cycle Fatigue (LCF) Life	—	4.0
Fracture Life	—	4.0
High Cycle Fatigue (HCF) Life	—	10.0*

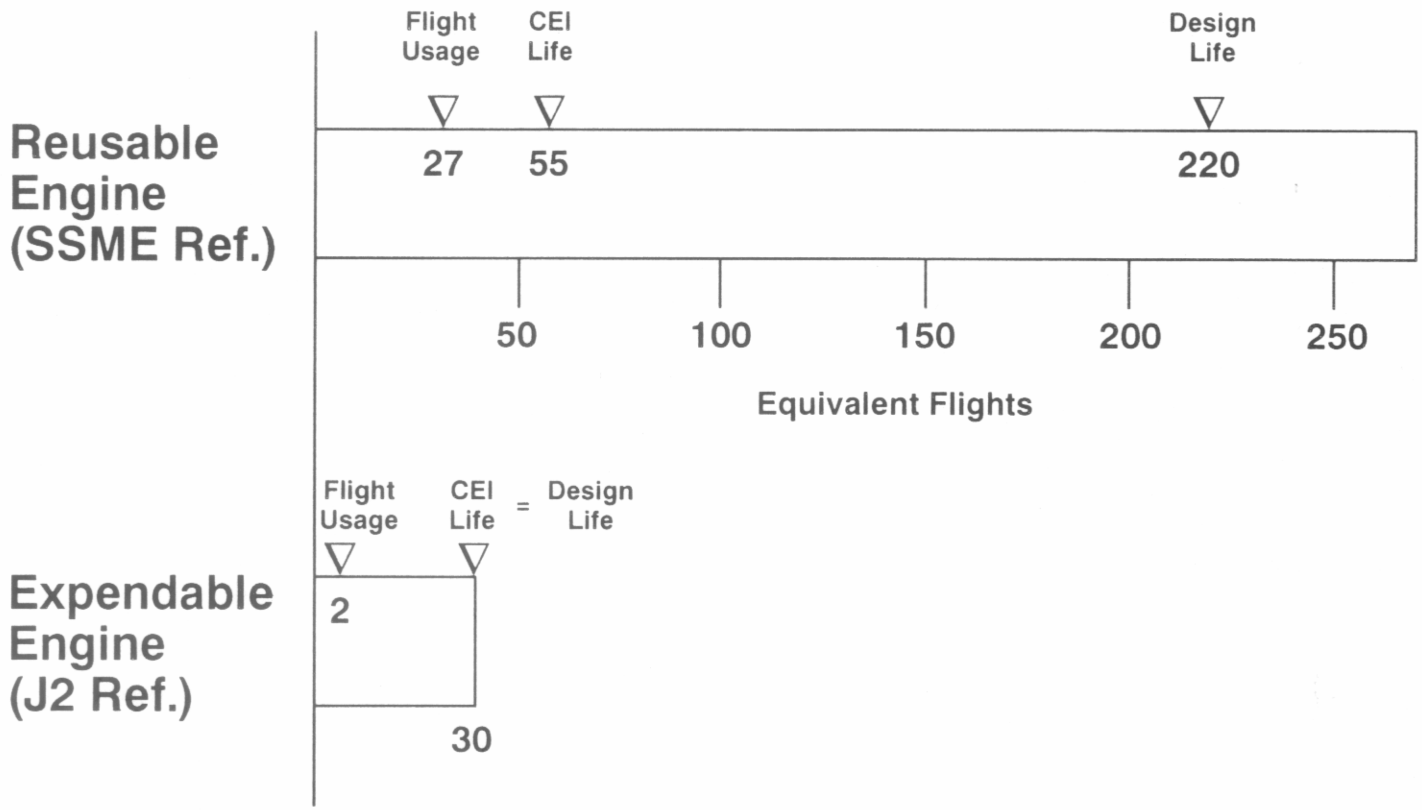
* Future Engines Will Use a Safety Factor of 1.4 at Design Life

Rocket Engine Life Analysis
High Cycle Fatigue

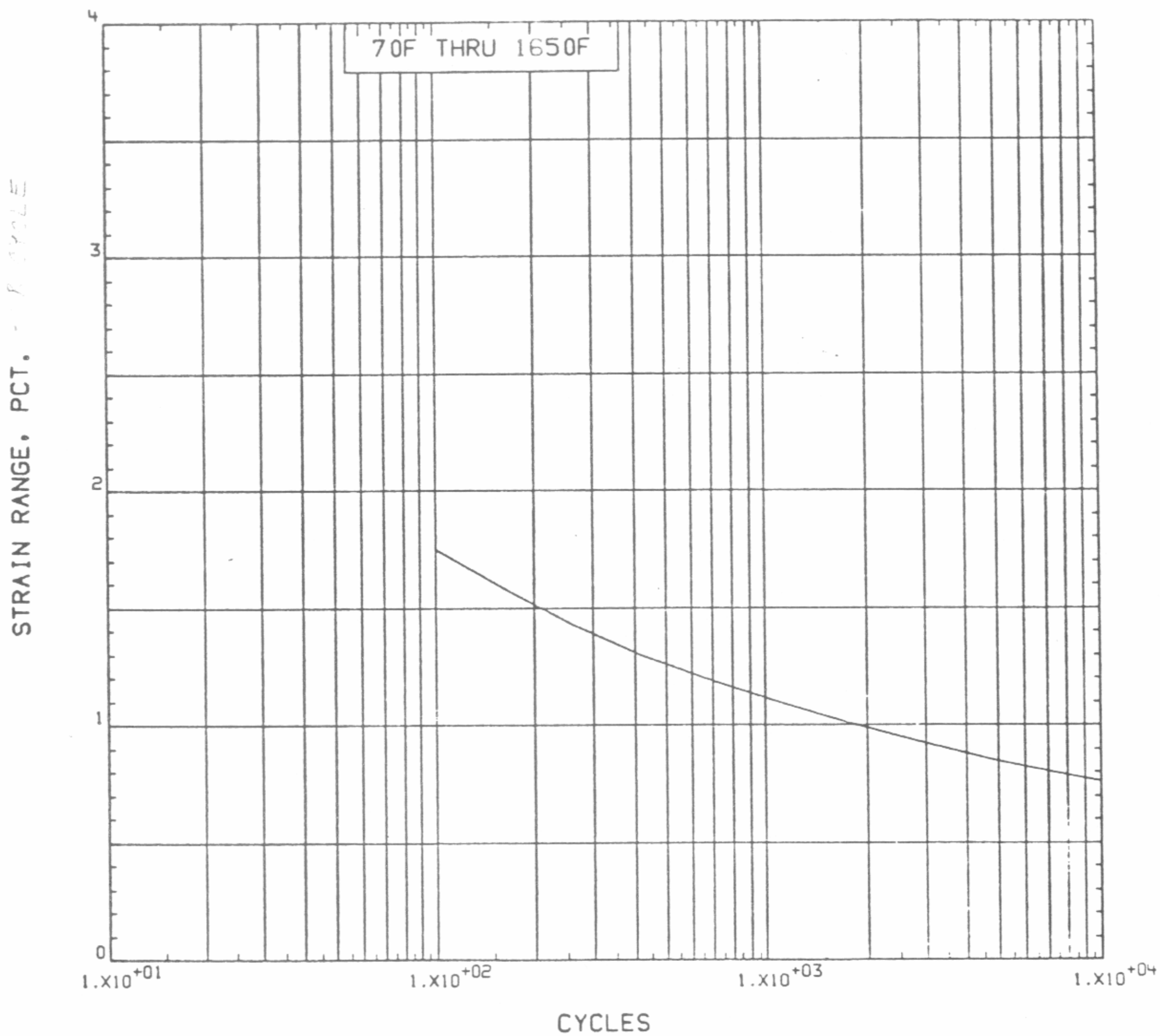


- Cycle Life Needed = Frequency x Firing Time x Number of Missions
- Properties Near Constant at Fixed Temperature for Range of Interest
  - $10^6 - 10^{10}$
  - 10 Times Life Yields Small Margin
  - 1.4 Safety Factor at Design Life Yields Large Margin
- For Given Design
  - Significant Life Improvement Possible by Temperature Reduction
  - Frequency Reduction Effective

Rocket Engine Life Analysis
Low Cycle Fatigue (LCF) Life Margin



Rocket Engine Life Analysis
Low Cycle Fatigue



- Moderate Reduction in Strain Range Can Produce a Large LCF Life Increase

- Small Unexpected Strain Range Increase Causes Severe LCF Life Decrease

Rocket Engine Life Analysis

Material Selection Considerations

	Expendable	Reusable
Tensile Yield and Ultimate Strength	X	X
Ductility	Minor	Major
Conductivity	X	Major
Low and High Cycle Fatigue	Minor	Major
Creep Strength (Stress Rupture)	—	Major
Hydrogen Resistance	Minor	Major
Oxidization Resistance	Minor	Major
Corrosion Resistance	Minor	Major
Wear Resistance	Minor	Major

Materials Selected for Reusability Dictated by Fatigue and Environmental Considerations

Rocket Engine Life Analysis
Major Life Limiting Factors

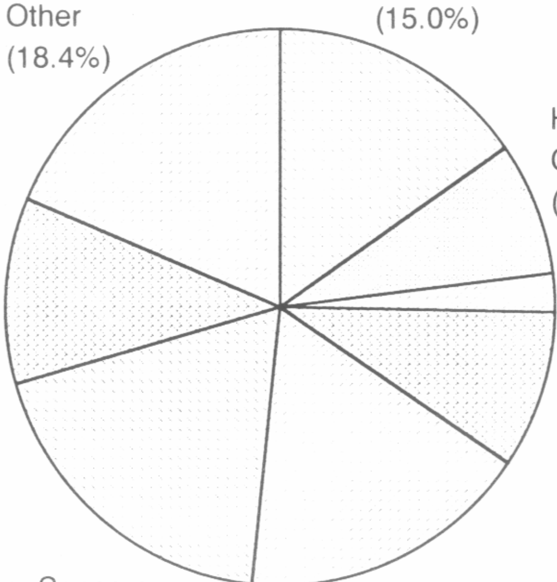
Component	Major Controlling Design Life Consideration
Main Combustion Chamber (MCC)	LCF, Blanching
Preburners	LCF
Injector	HCF (Posts - Coax) Loading (Impinging)
Heat Exchangers	HCF, LCF
Nozzle	LCF (Loading, ΔT)
Valves	HCF
Ducts	HCF
Low Pressure Pumps	HCF
High Pressure Pumps	HCF
Low Pressure Turbines	HCF
High Pressure Turbines	LCF, HCF, Bearing Wear

Reusable Engine History

Rocket Engine Life Analysis
Reusable Engine Life History

- One Database — SSME
- All Life information is Within the Context of SSME System
  - Given Start and Shutdown Sequence
    - Number and Placement of Valves
    - ASI "Pilot Light" Type of Ignition
    - Priming Volumes
    - Valve Leakages
  - Contact Bearings
  - Channel Wall MCC
  - Tubed Nozzle
  - Cooled Powerhead
- Good Information on Effect of Changing Pressure/Temperature/Flowrate Environment

Rocket Engine Life Analysis
Historical Subsystem Failure Fractions
SSME Phase 2



Subsystem	Failure Fraction
HPFTP	0.14965
HPOTP	0.07609
LPFTP	0.01745
LPOTP	0.0051
Nozzle	0.0908
Combustion Chamber	0.0908
Main Injector	0.0467
Preburners	0.03203
Sensors	0.07609
Propellant Controls	0.07609
Electronics	0.03203
Auxiliary Controls	0.01745
Ducting	0.10551
O_2 System Balance	0.0908
H_2 System Balance	0.0467
Human Judgment	0.0467

Typical Power Level Influence on Reliability

SSME Phase 2
100 to 109%

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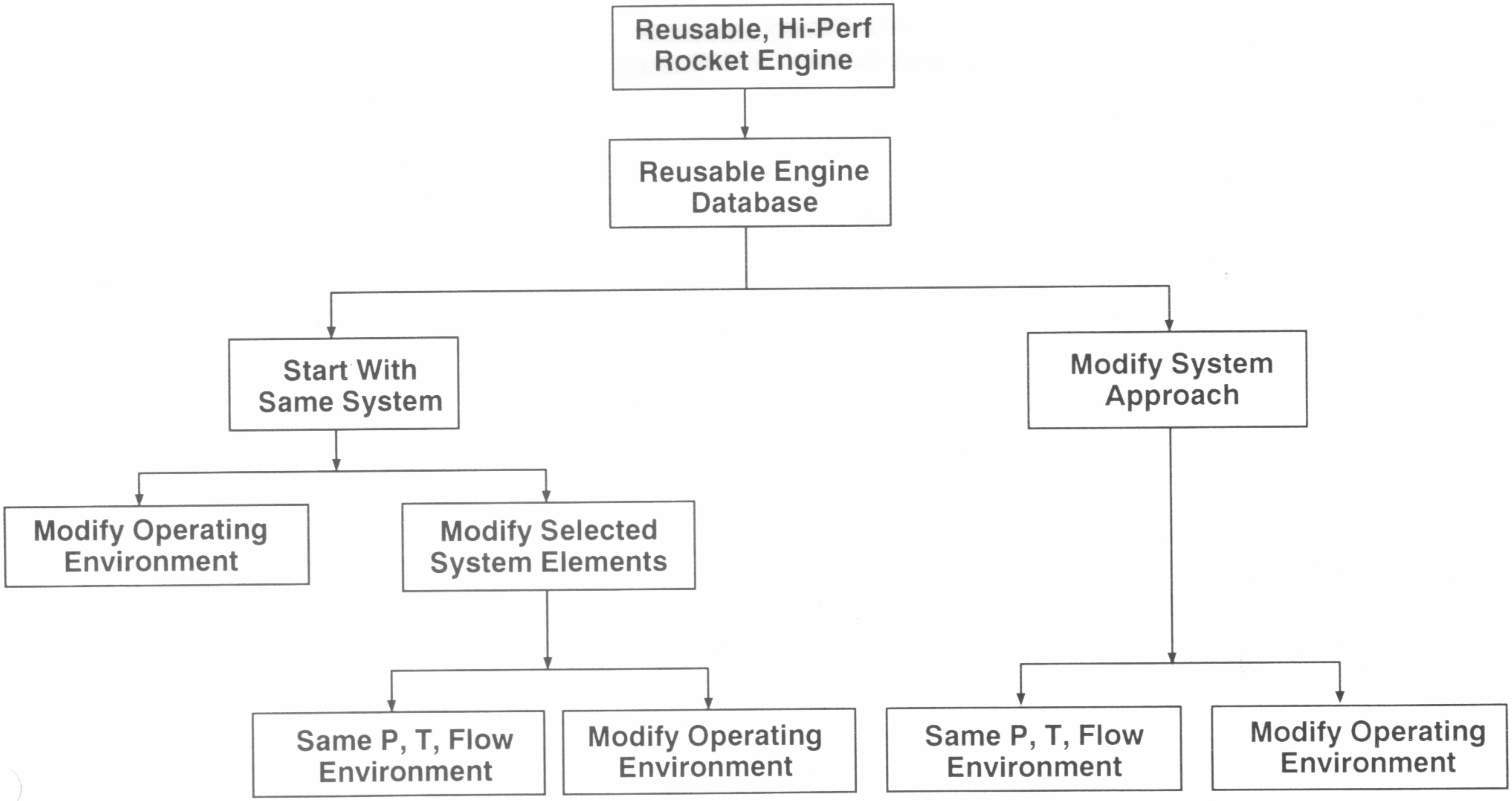
Life Extension Approaches

Rocket Engine Life Analysis
Two Approaches to Life Extension



Rocket Engine Life Analysis

Modify Operating Environment Approach

Basically a Margin Increase Approach

Rocket Engine Life Analysis

Modify Operating Environment Approach

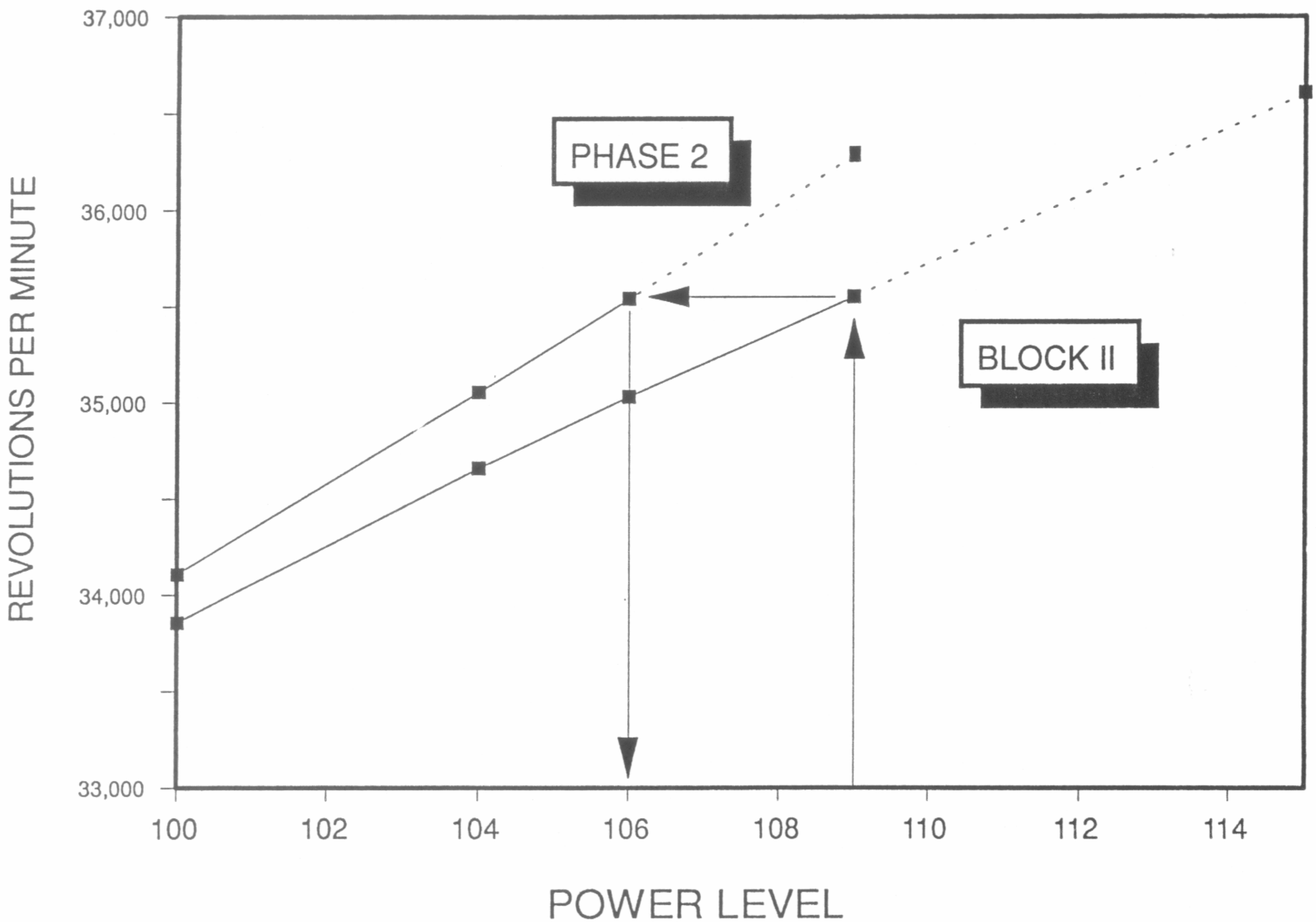
- Modify Operating Environment
  - Can Produce Very Significant Life Increase
  - Example Engine Studied for RLV Applications
    - A SSME Block II with Further Changes

- Methodology
  - Anchor to SSME Demonstrated Reliability
  - Include Quantified Improvement in Operating Environment

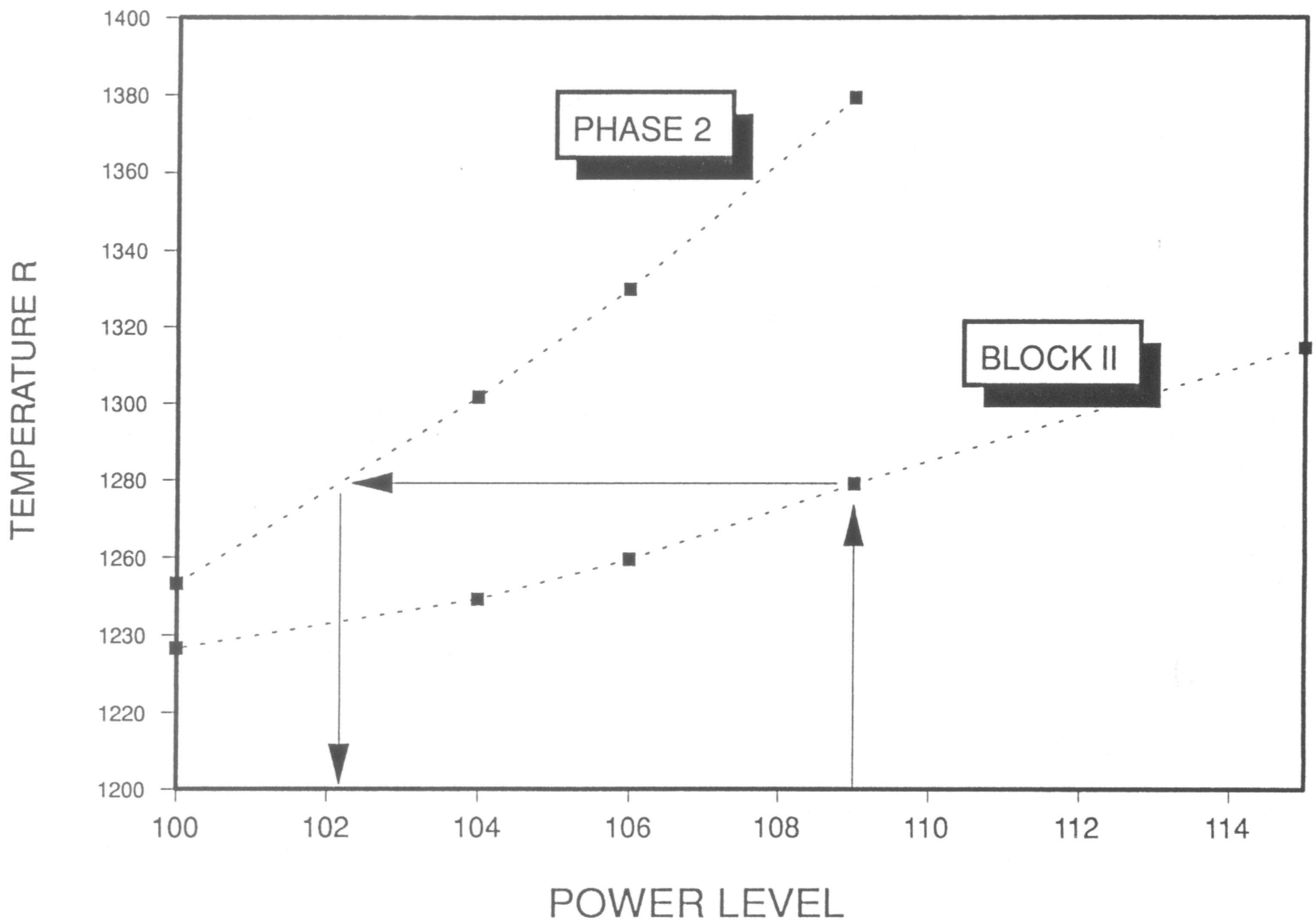
- Equivalent Power Level
  - Use Engine Power Balances
  - Pressures, Speeds, Temperatures, etc. that Affect Each Component
  - Compare to Current Flight Configuration (Phase 2)
  - Determine Equivalent Power Level for Each Parameter
  - Average the Parameters Applicable to Each Component

- Overall Engine
  - Weighted Average Equivalent Power Level
  - Weighted by Engine Reliability Model Failure Fraction
    - Example – Main Injector is 4.7% of the Unreliability
  - Account for Burn Time Differences
    - Historical Failures Follow Weibull Distribution with Beta = 0.5
    - Failure Rate Decreases with Burn Time

Rocket Engine Life Analysis
Parameter Equivalent Power Level
HPFTP Rotor Speed



Rocket Engine Life Analysis
Parameter Equivalent Power Level
HPOTP Turbine Discharge Gas Temperature



Rocket Engine Life Analysis
Component Equivalent Power Level Examples

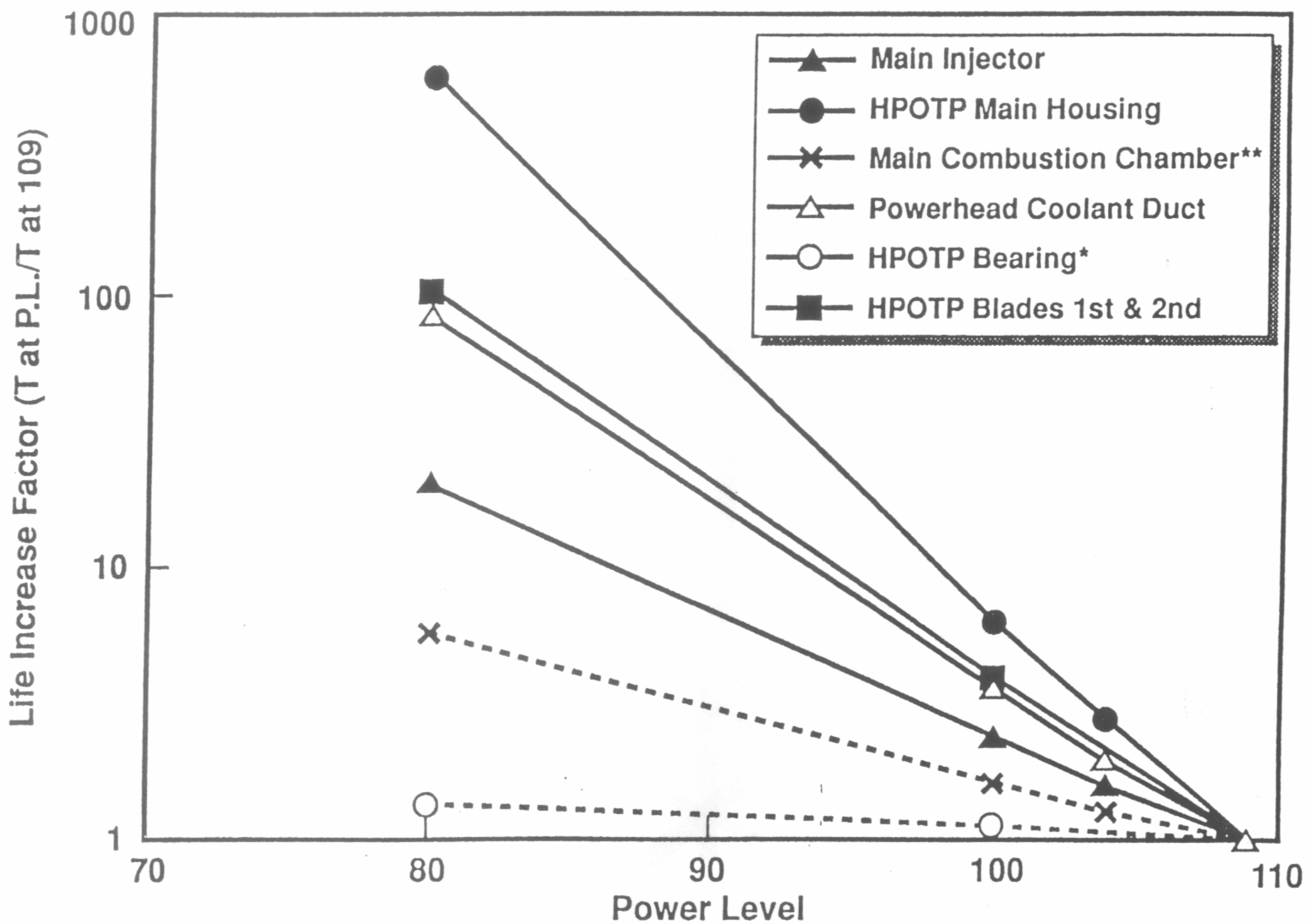
- High Pressure LOX Turbopump

• Engine LOX Flowrate	103.8
• Turbine Gas Temperature	99.5
• Preburner Chamber Pressure	98.0
• Rotor Speed	80.1
• Inlet Pressure	72.2
• Discharge Pressure	99.1
• Preburner Pump Discharge Pressure	101.3
• Turbine Torque	112.9
Average	***95.9***

- Preburners

• High Pressure LOX Turbine Temperature	99.5
• High Pressure Fuel Turbine Temperature	80.0
• Oxidizer Preburner Chamber Pressure	98.0
• Fuel Preburner Chamber Pressure	97.9
Average	***93.8***

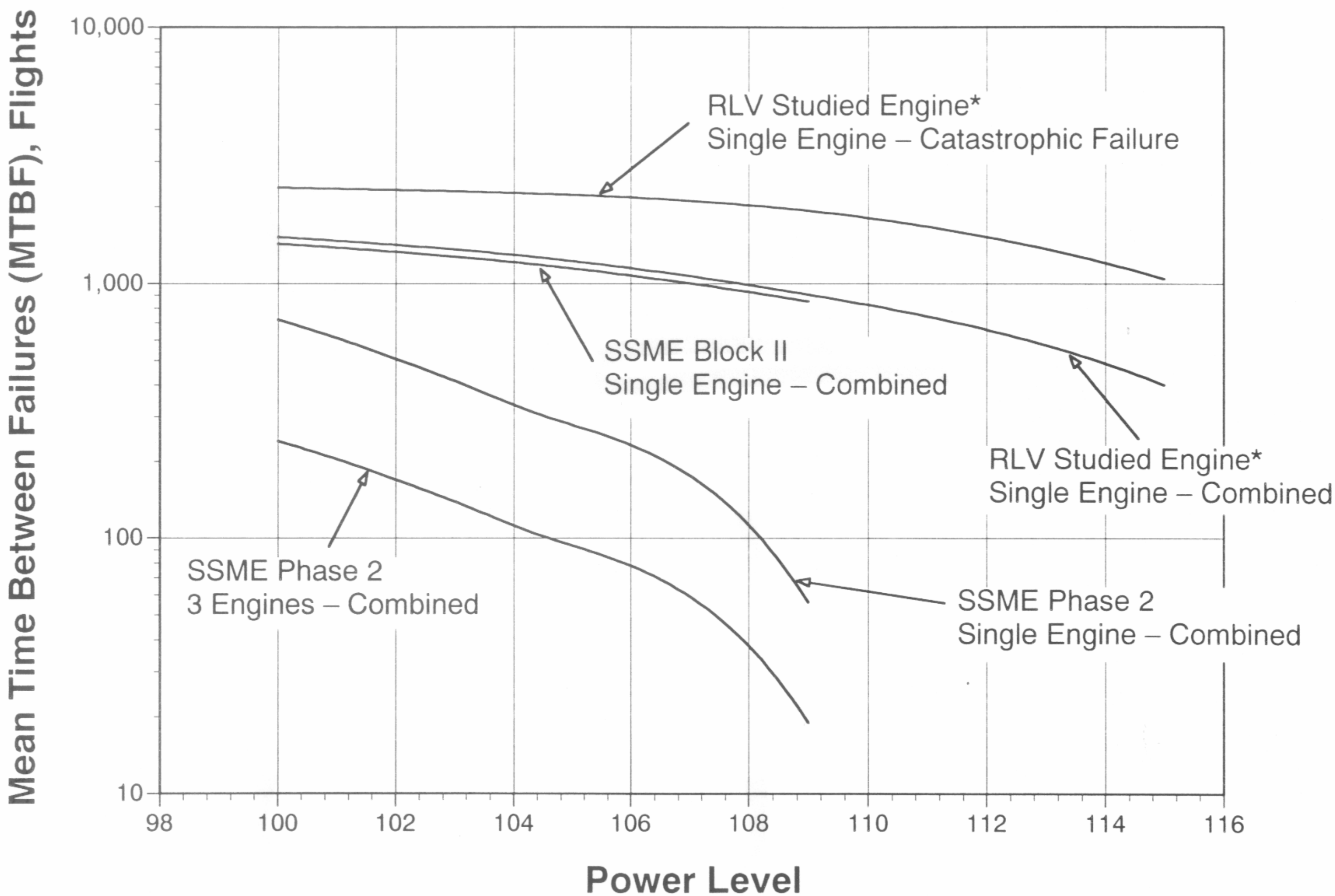
Rocket Engine Life Analysis
Typical Power Level Influence on SSME Life
Phase 2



* Hydrostatic bearing eliminates this life limit
** Large throat MCC eliminates this life limit

Engine Reliability Impact

50% Confidence



* Would be reduced 29% if burn time is doubled from 200 sec to 400 sec

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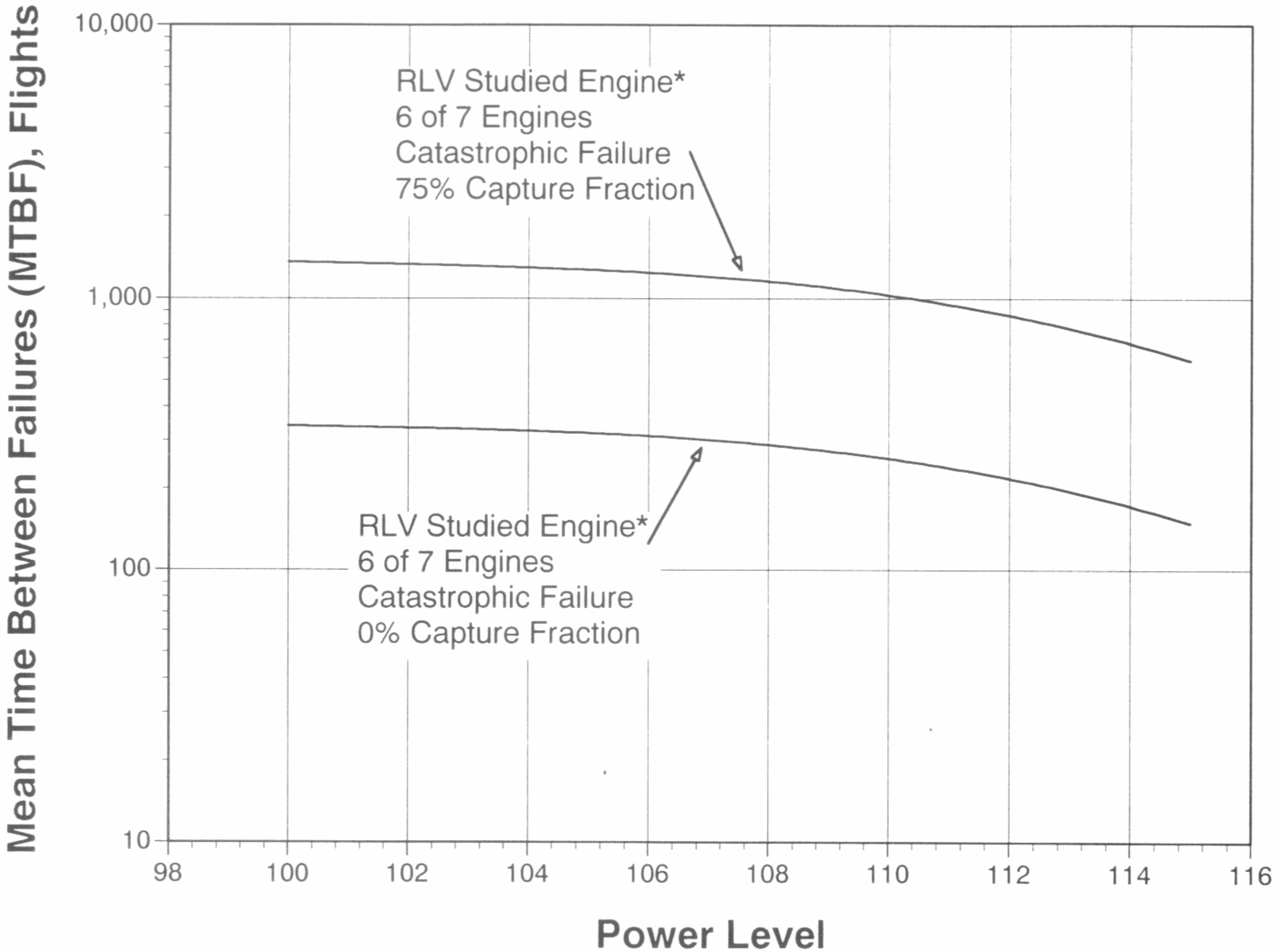
Engine Reliability Impact

Multiple Engines With Engine Out Capability
50% Confidence

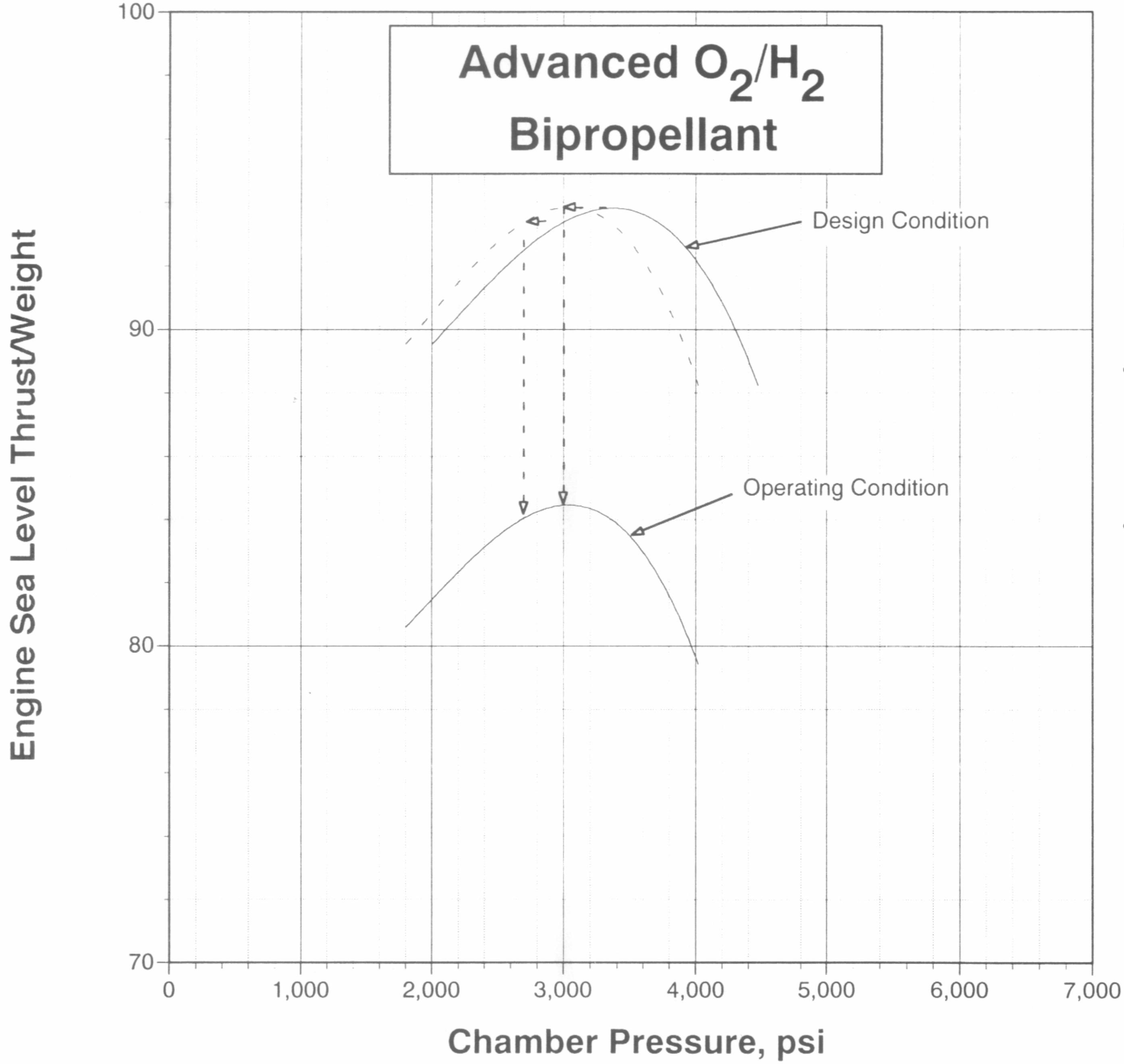


Capture Fraction – Percentage of Catastrophic Failures which are Captured by Health Management System Producing a Shutdown of the Engine (Engine May or May Not be Damaged)

* Would be reduced 29% if burn time is doubled from 200 sec to 400 sec

TA3–1911b

Engine Sea Level Thrust/Weight



Effects on Sea Level Thrust/Weight of Margin Inclusion

- Operate at 90% of Design Thrust and Chamber Pressure
- Very Large Increase in Engine Life
  - Turbine Temperatures
  - Pressures
  - Vibration Environment

TA3–1906

Rocket Engine Life Analysis

Modify System Approach

This Approach Can Remove Specific Significant Life Limiters

Rocket Engine Life Analysis

- Engine Cycle Choice
  - Strong Impact on Operating Temperatures
  - Strong Impact on "Cost" of Power Margin

Rocket Engine Life Analysis

Closed Cycle Thermodynamic Capabilities

Cycle	Added Energy (Combustion) Fuel Side	Added Energy (Combustion) Oxidizer Side	Flows Used Fuel	Flows Used Oxidizer
Dual, Mixed Preburners	√	√	√	√
Dual, Fuel (or Ox) Rich Preburners	√	√	√	Part
Single Preburner/ Expander	√	—	√	Part
Single Preburner Expander	—	√	√	Part
Expander	—	—	√	None

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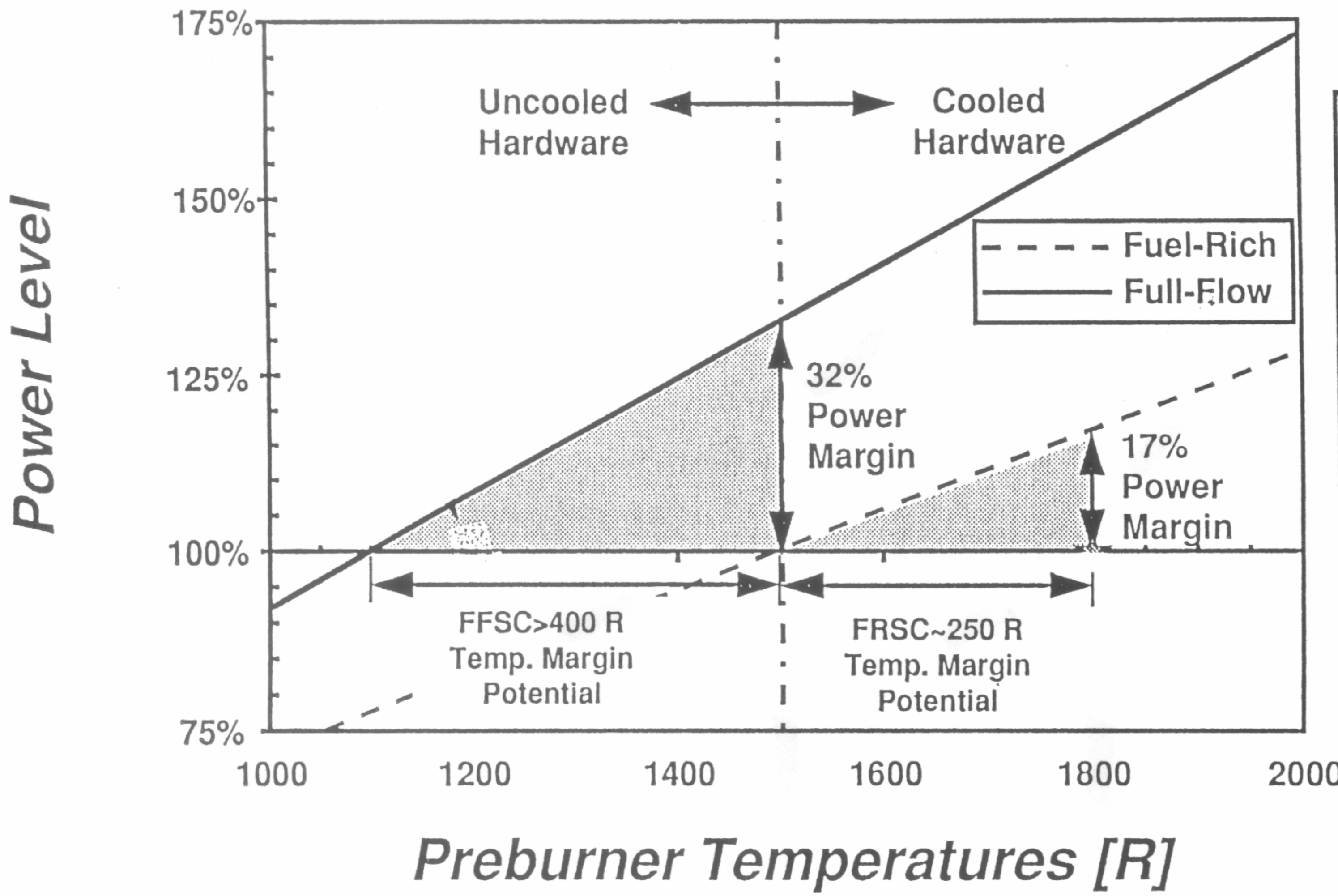
Engine Cycle Choice Can Provide Increased Design Margins and Opportunity for Future Growth



Potential Margin Uses

- Design Maturation
- Increased Mixture Ratio
- Increased Pc
- Deep Throttling

TA3–1125

Turbomachinery

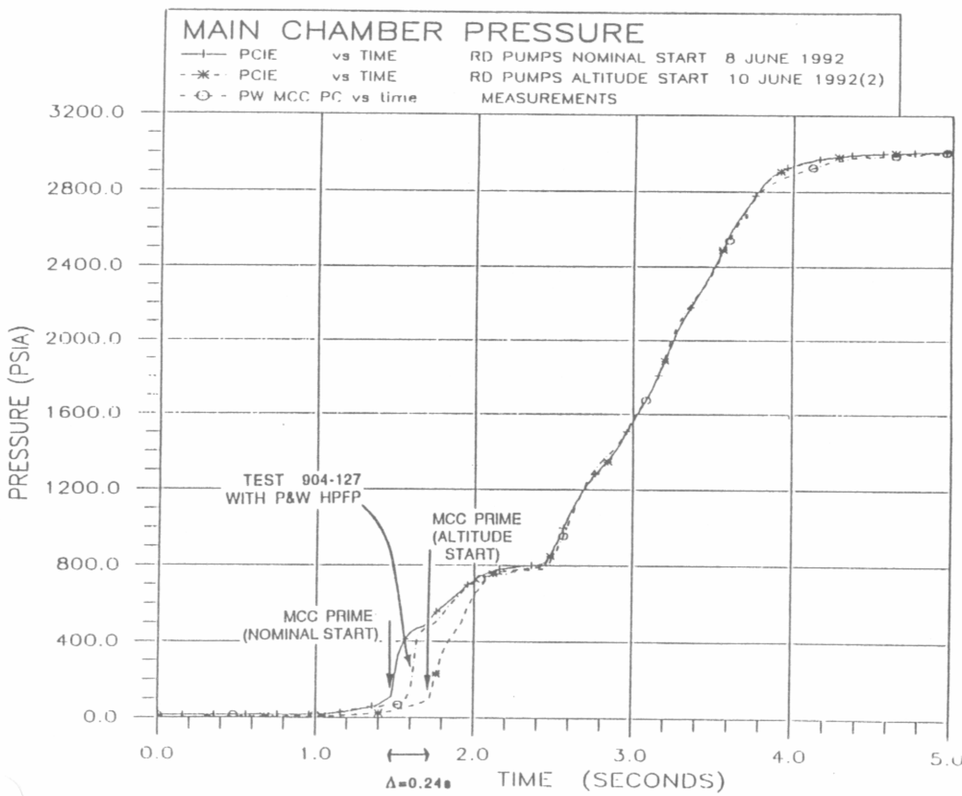
Rocket Engine Life Analysis
Turbomachinery

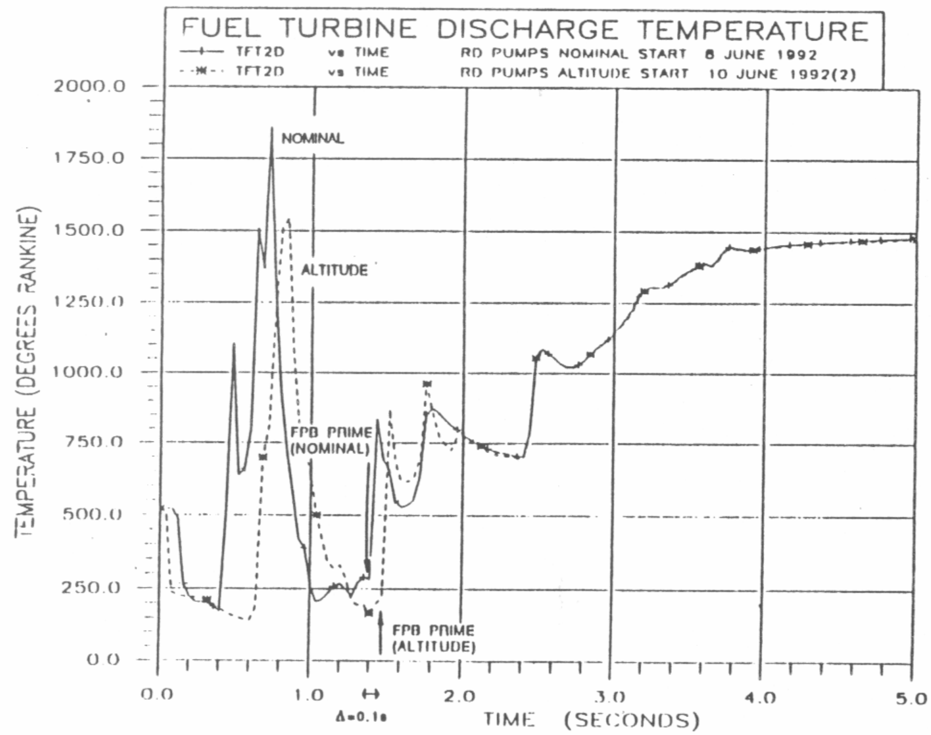
- Blade Vibration
- Bearing Wear
- Thermal Environment
  - Start Temperature Spike
  - Inhomogeneous Flow Across Blade
  - Shutdown Quench
- Seals
  - Rubbing
  - Leakage
  - Lift-Off Wear
- Sheet Metal
  - Flow Induced Vibration

Rocket Engine Life Analysis
Turbomachinery Life Examples

- Significantly Change Low Cycle Fatigue Life Limit
  - System Change
- Parts Count and Design Approach
  - Design Change

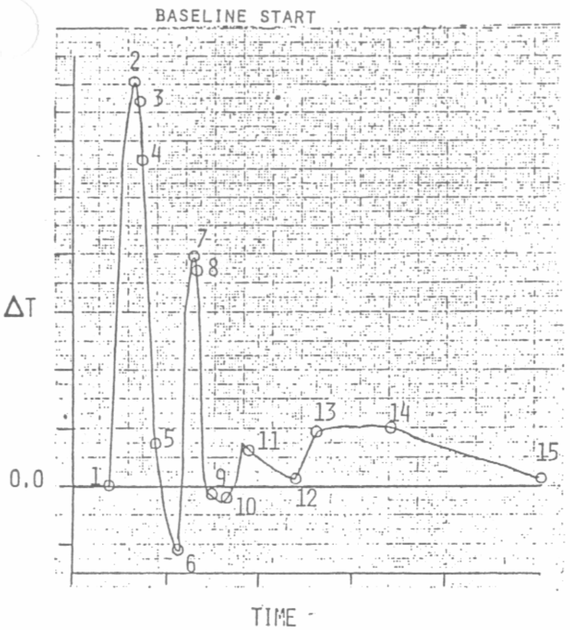
Rocket Engine Life Analysis
SSME Start

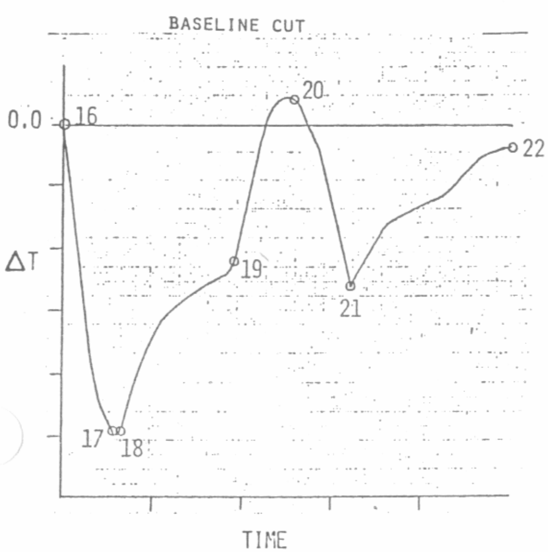


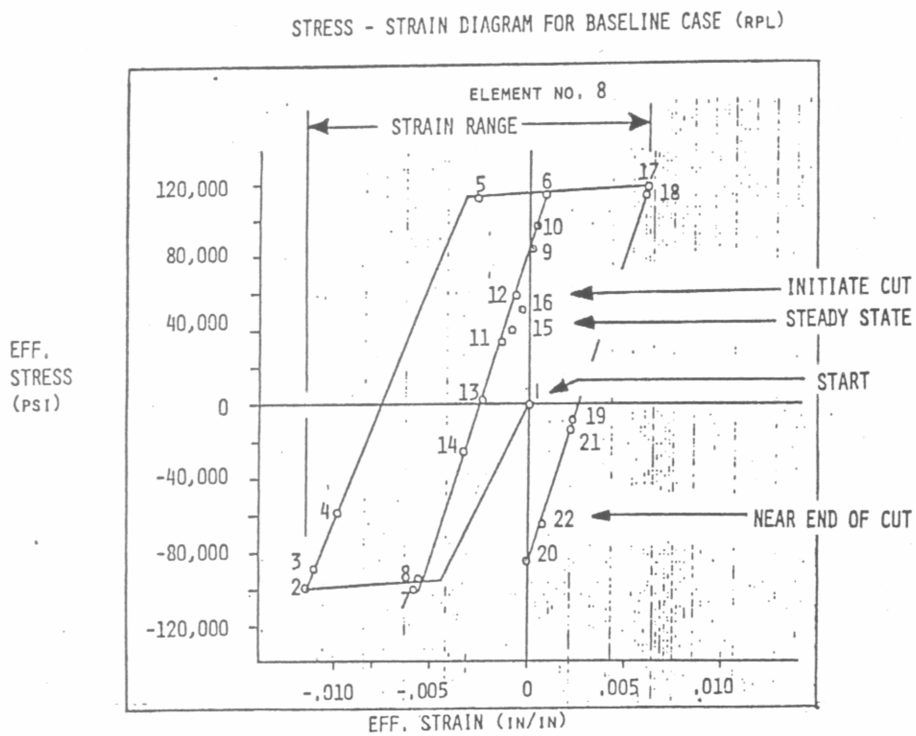


Rocket Engine Life Analysis

Turbine Low Cycle Fatigue

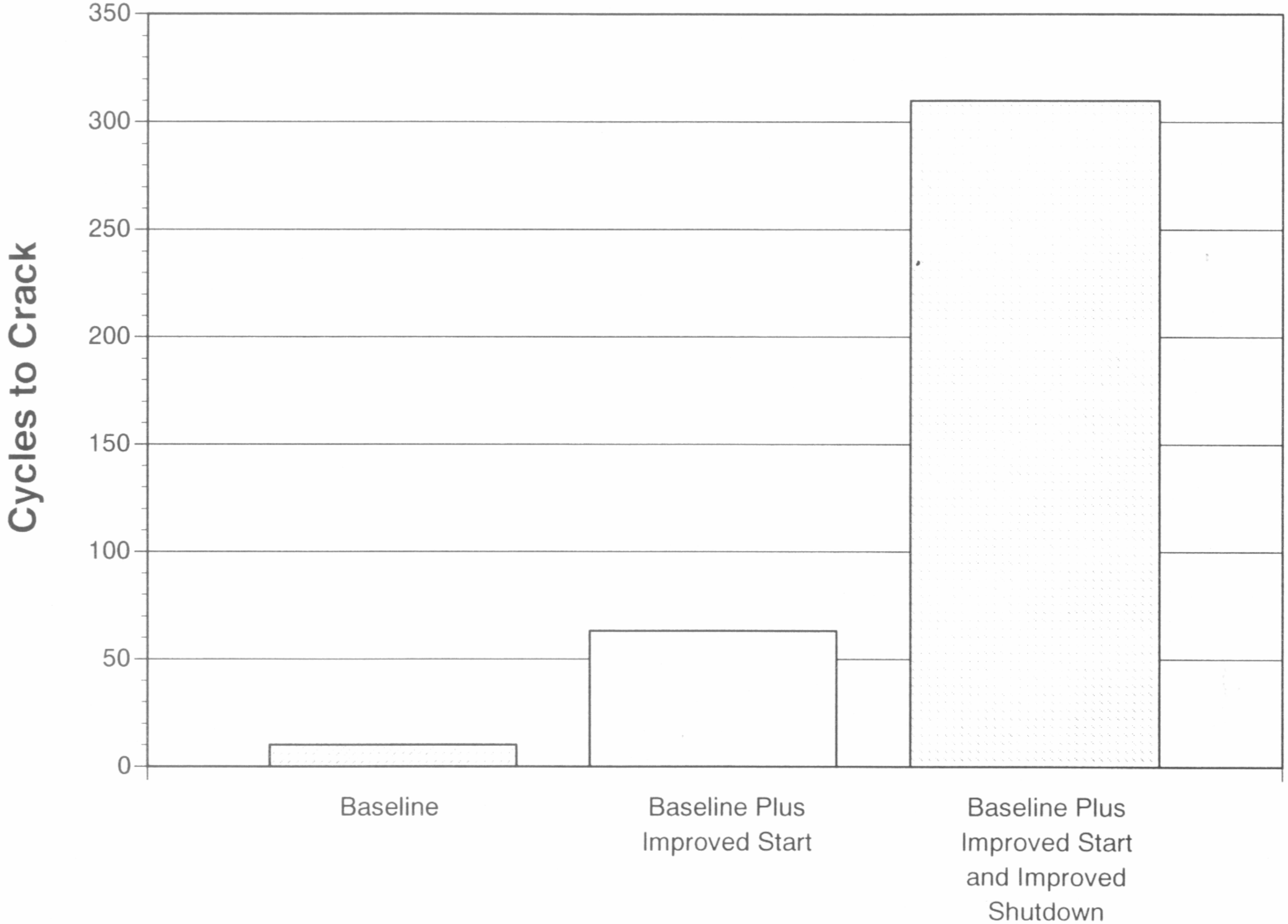






- Stress/Strain for One Full SSME Cycle
- HPFTP 1st Stage Nozzle Leading Edge
- ΔT = (Surface - Bulk) Temperature
- **The Strain Range is Defined by First Temperature Spike (1 - 2) and by Initial Part of Quench (16 - 17)**

Engine Life Impact of Changing Start and Shutdown Sequence



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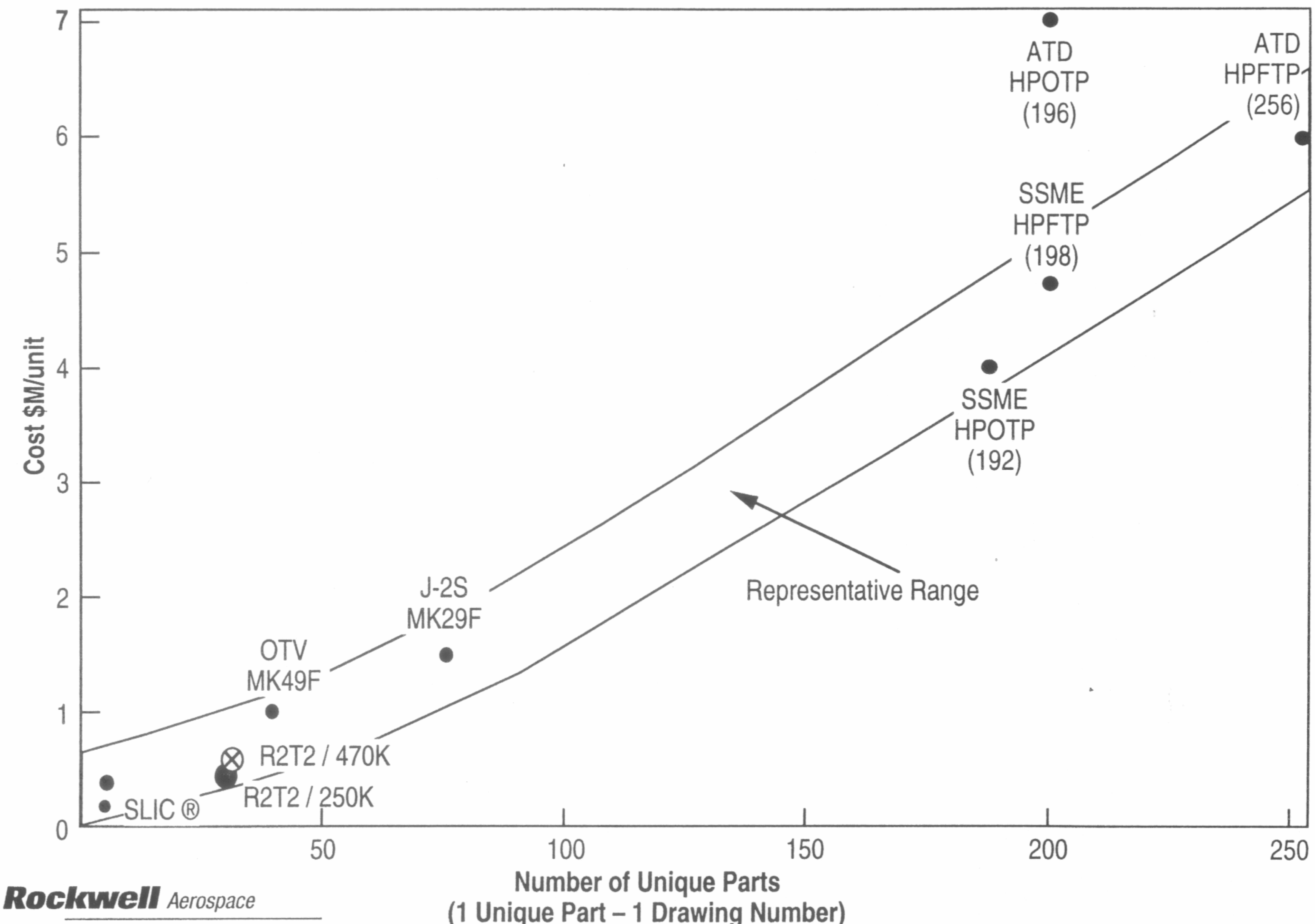
LOW UNIQUE PART COUNT REDUCES UNIT COST AND SHOULD LOWER LIFE CYCLE COST



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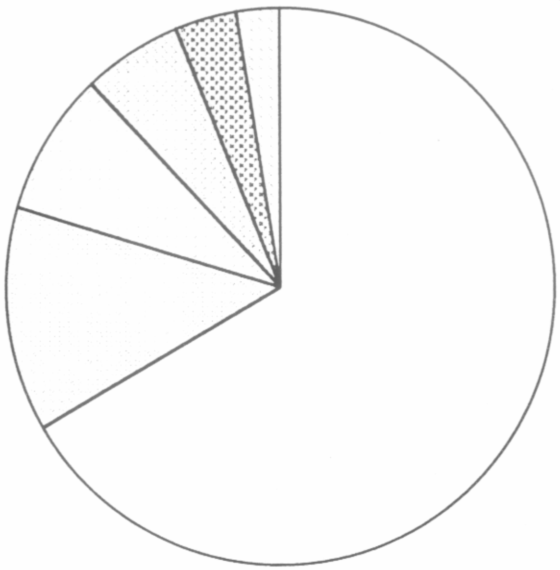
Rocket Engine Life Analysis
Turbopump Design Changes Reduce Removal for Cause

High Pressure Oxidizer Turbopump



- Change to New SLIC® Based RRTT Design and Modify System Cycle to Mixed Preburner Full Flow Staged Combustion Cycle
  - Eliminates ~ 90% of Removals for Cause
    - Simpler, Much Lower Part Count Turbopump
    - Lower Turbine Temperatures
    - Much Higher Power Margin

66.6%	Bearings	• Hydrostatic Bearings Eliminate Rolling Element Bearing Wear • Reduced Turbine Temperature from 1560 °R to 1180 °R Improves Materials Strength and Extends Life
13.0%	Blades	
8.4%	Tip Seal Retainer	• Eliminate Tip Seal and Use Large Turbine Blade Clearance
6.0%	Handling	
3.6%	Contamination	
2.4%	Disk Life	• Eliminate Disk Plating and Use LOX Compatible Haynes 214

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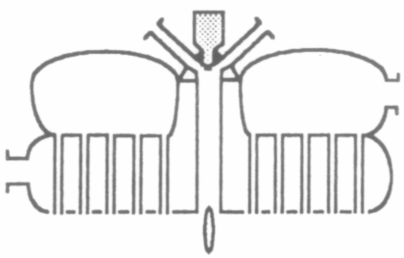
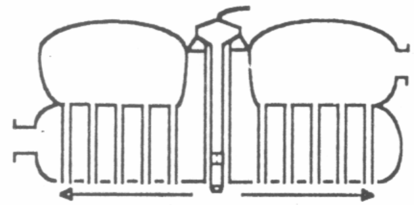
Combustion Devices

Rocket Engine Life Analysis
Ignition Systems



Single Point Ignition
- Augmented Spark (SSME)
- Infrared Laser
- Catalytic



Multipoint Ignition
- Ultraviolet Laser

- Multipoint UV Laser
  - Decouples Start and Shutdown from Flammability Limits
  - More Freedom in Closed Cycle Start Sequences
    - Flammability Limits
    - ASI Priming
  - Helps Eliminate Start Temperature Spike
  - Can Reduce Pressure Loads at Start

Rocket Engine Life Analysis
Combustion Devices

- Main Combustion Chamber (MCC)
  - Limited by Low Cycle Fatigue
    - Strain
      - Driver is ΔT Across Liner Wall
        - "Creep Ratchet"
          - Compressive Strain at Mainstage with Creep
          - Followed by Tension at Shutdown Which Thins Wall
    - Blanching
      - Occurs at Hot Spots Along Wall
      - Complex Chemical Interaction Which Decreases Material Properties
      - Creep Ratchet Then More Effective in Producing Damage

Rocket Engine Life Analysis
Combustion Devices (Cont'd)

- Hot Core Inherent in High Performance Rocket Engine
  - System Changes Marginal
    - Film Cooling
      - Performance Cost
  - Hardware Design Changes Very Effective
    - Lower ΔT
      - Increase Heat Transfer
        - Increased Number of Coolant Channels
        - Thinner Walls
        - Channel Shapes
    - Coatings to Reduce Blanching

- RLV Designs Use Increased Number of Coolant Channels, Thinner Walls to Decrease Strain, and Coatings to Reduce Blanching

- Preburners
  - Reduce Temperature and Run Uncooled
  - Use Channel Wall Instead of Sheet Metal
    - Eliminate HCF Damage at Hidden Joints

Rocket Engine Life Analysis
Nozzles

- Tube Cracks
  - Replace Tube Wall With Channel Wall for Low Area Ratio Portion of Nozzle
    - Area of High Heat Flux and Pressure
  - Move MCC/Nozzle Attachment to Higher Area Ratio
    - Lower Pressure at Joint

- Side Loads
  - Optimum Area Ratio for Single-Stage-to-Orbit Vehicles Lower than SSME
    - Significantly Reduced Loads
  - For Given Area Ratio
    - Materials
    - Reinforcement
    - Dual Position Nozzle

Controller, Sensors, Valves,

Health Management

Rocket Engine Life Analysis

Controller, Sensors, Valves, Health Management

- Current
  - Controller — 10 Years Storage, 8 Hours Flight Operation on SSME
  - Sensors — Design Sensors for Rocket Applications
    Harness Problems
    Flow Induced Vibration Produced in Other Components
  - Valves — 12,000 Crank Cycles on SSME
    - About 100 Flights

    Careful Design Needed in Seals, Bearings, Actuators
    Early, Extensive Qual Testing

- Life Extension
  - Use Redundancy
  - Componentry Is Not Main Problem
  - Design Integration With, and as, a System is Key

HRST Engine Must Have Health Monitoring System (HMS), With its Associated Sensors, Designed at Program Inception

- Sensors Designed to Support HMS and Designed With Components and to Minimize Flow Induced Vibration
- Harnesses Designed to Minimize Handling

Mitigation Approach Summary

Rocket Engine Life Analysis
Turbomachinery

Life Limiter	Mitigation Approach	Potential Drawback or Interaction
Turbo-Machinery blade fatigue	Modify Start/Shutdown (reduce temporal gradients)	Flight Heritage
	Lower Power Density	Reduced System Performance or Increased Stages
	Reduce turbulence	Weight Complexity
	Stiffer, more robust design	Weight Cost
	Ceramic Blades	Cost Technology Readiness

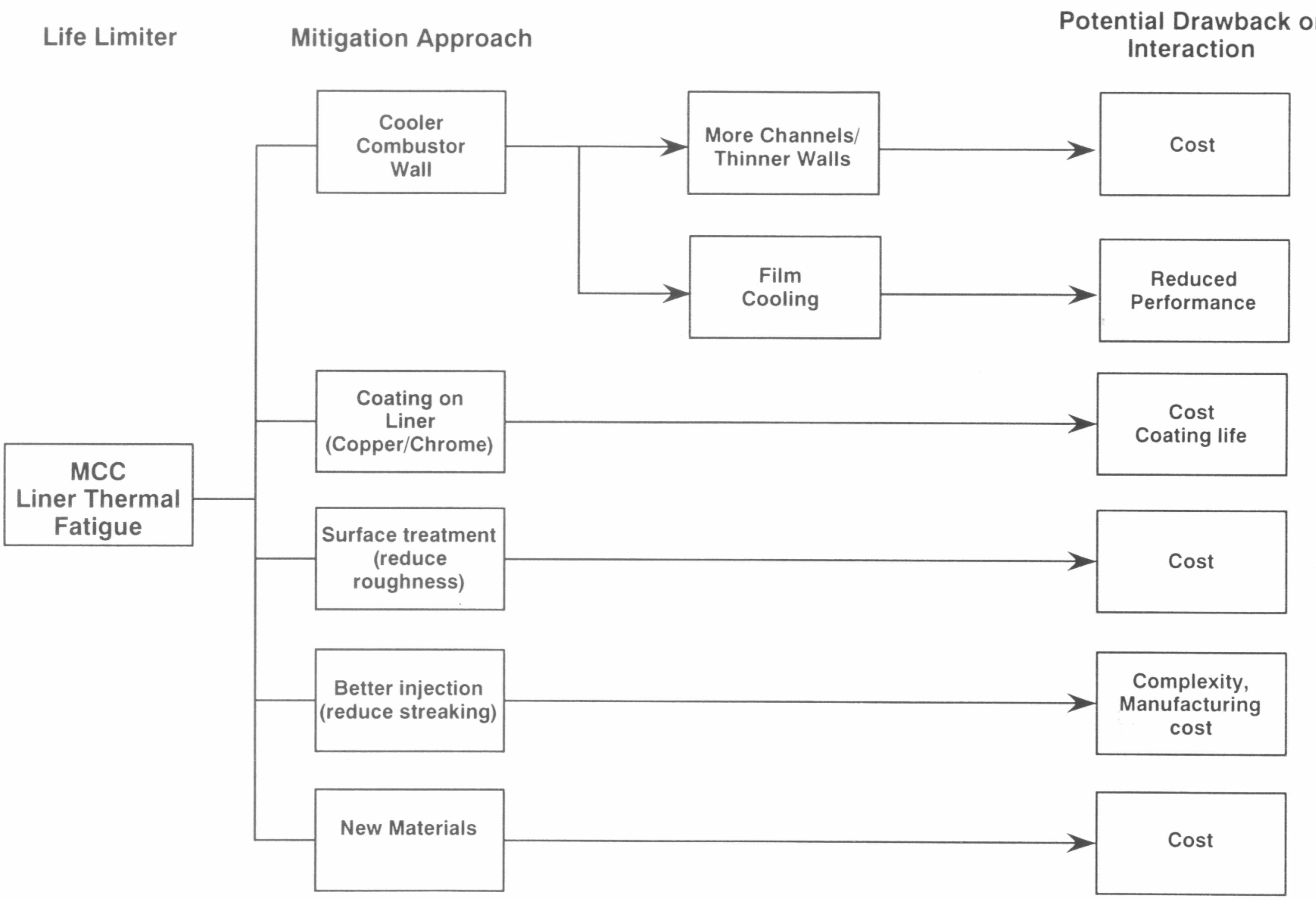
Rocket Engine Life Analysis
Turbomachinery

Life Limiter	Mitigation Approach	Potential Drawback or Interaction
Bearing Life	Hydrostatic (Fluid film) Bearings	Flight Heritage
Seal Life	Similar Fluids in Turbines and Pumps	Oxygen Environment
Blade Thermal Fatigue, Erosion/ Corrosion	Modify Start/ Shutdown	Flight Heritage
	Lower Operating Temperature	Cycle Change
	No streaks (better mixing)	Component Size & Weight
	Coatings	Cost Coating durability
	Smoother, more complete control	Increased valve count, complexity, Control algorithm
	Ceramic Turbine Blades	Cost, Flight Heritage

Rocket Engine Life Analysis
Turbomachinery

Life Limiter	Mitigation Approach	Potential Drawback or Interaction
Turbo-Machinery Sheet metal fatigue	Modify Start/Shutdown (reduce temporal gradients)	Flight Heritage
	Eliminate sheet-metal where possible	Cycle Choices
	Reduce turbulence	Weight Complexity
	Stiffer, more robust design	Weight Cost
	Lower Power Density	Weight
	Better fastening technology	Cost Weight

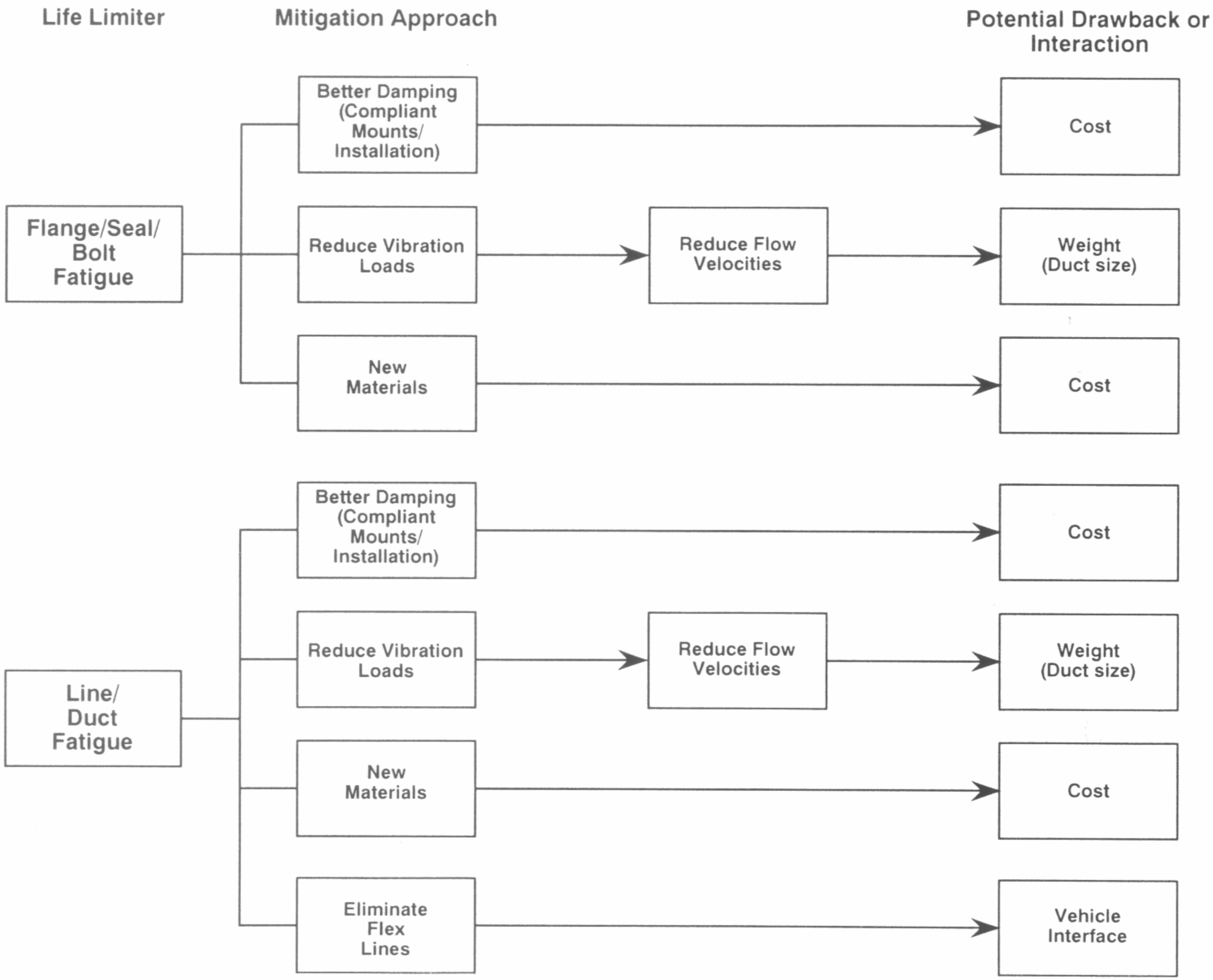
Rocket Engine Life Analysis
Main Combustion Chamber



Rocket Engine Life Analysis
Nozzle

Life Limiter	Mitigation Approach	Potential Drawback or Interaction
Nozzle Tube Cracks	Channel Wall Construction (Partial/Full)	Weight
	Higher Area Ratio Attachment	Weight
	Improve Alignment during Assembly	Cost
	New Materials	Cost
Nozzle Side Loads (Flow sep)	Structural Reinforcement	Cost Weight
	Movable Nozzle (extendible)	Cost Weight Complexity
	New Materials	Cost

Rocket Engine Life Analysis
Lines and Ducts



Summary and Conclusions

Rocket Engine Life Analysis
Summary

- Design Out Specific Problems Discovered During STS/SSME Program

and

- Modify Operating Environment

> - Produce High Performance Rocket Engine Lives Consistent With RLV Goals
>   - 20 - 50 Flights Between Overhauls
>   - 100 Flight Life

- Add Power Margin

> - Produce Lives Consistent With HRST Goals
>   - 200 Flights Between Overhauls

Rocket Engine Life Analysis
Conclusions

- Methods Are Known to Extend High Performance Rocket Engine Life Beyond Current Reusable Practice
  - 100's to 1000's of Flights
  - Design Out Life Limiting Lessons Learned from STS/SSME Program
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    - Combustion Chambers with Lower Wall Temperatures
    - New Materials
  - Different Combinations of These Techniques Produce Varying Degrees of Life Extension But All are Not Applicable to All Designs
- HRST Goal of $\geq$ 200 Flights Between Propulsion System Overhauls Appears Very Feasible